FEATURE ARTICLE

Storyboarding for Biology: An Authentic STEAM Experience

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Abstract

We introduce biology to the artist's design tool, the storyboard. This versatile organizing and visualizing artistic platform is introduced into the biology classroom to aid in an inventive and focused discovery process. Almost all biological concepts are dynamic, and storyboards offer biology, lecture, wet and computational labs, flexibility, inventiveness, and an opportunity for students to slow down the so-called steps of biological processes and moderate their observations. Storyboarding is a thoughtful and reflective discovery device with enormous potential to break with traditional biology classroom experiences and return to the root of the educational process: storytelling. It will encourage teachers to embark on the remodeling of the biological curriculum with specific technical skills that students and teachers should consider developing to make the STEAM experience tailored to the uniqueness of biological systems. Storyboards offer hands-on, illustrative, and interactive conversations about biology concepts. They are an "unplugged" and contemplative experiences, organizing frameworks for personal expression focused on biological wonders.

Key Words: *storytelling; evolution; change; dynamics; focused observation; sketching.*

○ Introduction

Imagine a protein over millions of years with mutations accruing; natural pressures wavering and fluctuating in time; amino acids shifting; and anions, cations, interface, and active sites transitioning subtly. When we picture this in our mind, we might see stages word by word and ideas concept by concept. Our mind forms and feels shapes of what we perceive as a biological entity, perhaps a protein. Words establish momentary static images. Those images can morph, blend, and, overlap in our mind's eye. They are reminiscent of current graphics, textbook visuals, maybe graphs and statistical data, a mélange of our visual-language perspective. Similarly, describing the growth of a pumpkin seed planted in the soil can trigger thoughts about the rhizosphere, early cellular respiration, exchange of oxygen, and a myriad of protective metabolic activities, with nutrients and genes emerging from dormancy and activating mitosis.

We all know that it is difficult *not* to imagine a pink elephant dancing once we've read or heard the suggestion. In biology, arbitrary boundaries are established by perceived events and so-called stages of biological processes we cannot see or know that inform our perception of those processes, where they begin and where they might cycle back to or "end" (Mnguni, 2014). The storyboard can help us explore and evaluate the process and dynamic relationships. Storyboards help us appreciate the complexity and transitional nature of these systems because we must slow them down and assess the data and our own perception of the data. What tools do educators have to accomplish this critical introspective observational task? How can we avoid micromanaging student experiences with knowledge and promote building and instilling thoughtful discovery? The answer lies outside of biology and in the arts, with a common organizing format known as the storyboard. Creating a physical storyboard is the artistic *proto-slow* of escalating amounts of data and visual information. In biology, storyboarding can allow students to take the knowledge they've "soaked up" and reinterpret it at a relaxed, illuminating pace. This can change how we teach, convey, learn, and think about biological information and the conceptualization of biological dynamics.

Storyboards help artists organize seemingly multilayered, excitable events, assisting them in conceptualizing weblike interactions.

○ What Is Storyboarding?

Storyboarding is a method of organization that artists use to develop action and frames of change or motion. Storyboards flesh out dynamic processes and offer possibilities. A storyboard provides angles, perspectives, and views to create a visual flow of a story as the artist sketches out ideas about interacting elements within a

The American Biology Teacher, Vol. 84, No. 6, pp. 328–335, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2022.84.6.328.

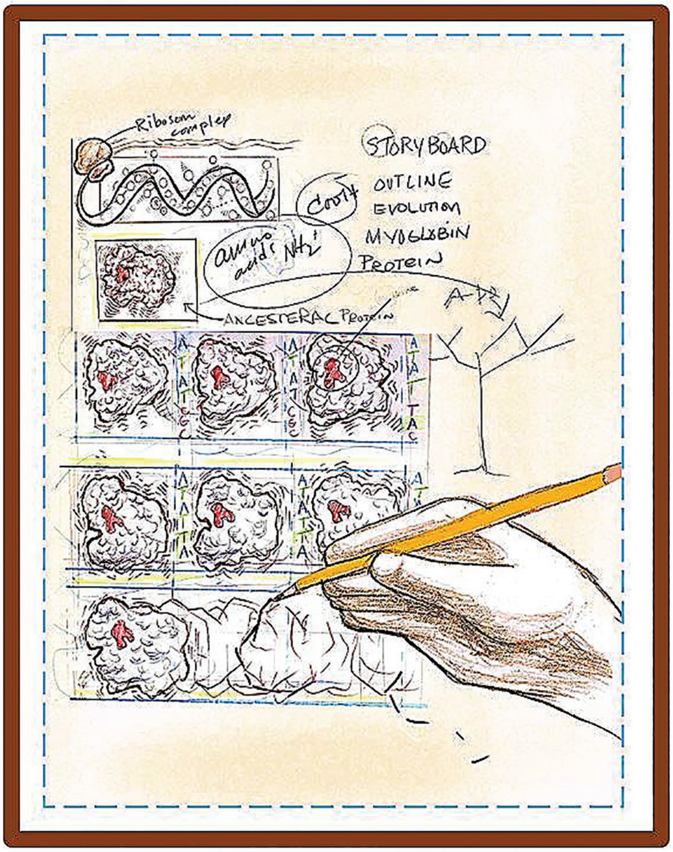

Figure 1. Sketching a storyboard for protein evolution.

frame. Advertisements, movies, theaters, and graphic novels use storyboarding to anticipate and plan scenes (Price & Pallant, 2015). In this article, storyboarding takes on a new meaning for the biological sciences. One of the key components of the storyboard framework is sketching. Sketching complements the boundaries of the frame in a storyboard by "fleshing out" the ideas that go in it. Historically, sketching has been essential to "capturing" the astute observations of the biologist. Sketching is also the activity where much of the development of an idea happens. Sketching skills, however, must be developed. The storyboard template or frame influences the sketches, and the sketches influence the composition of the storyboard. It can help students, teachers, and researchers narrow and expand their perception of a phenomenon as a learning tool. By storyboarding a particular subject, we can dissect it and reinterpret the concept (Tumminello, 2005). Figure 1 is an example of a layout for changes over time in a generic protein. The storyboard sketches imply that the protein is moving or changing and that "action" is happening.

Sketching plays a critical role in pausing the action to analyze. If done correctly, sketches capture movement. They capture subtle changes, forces, ranges, and contrasted actions (Hale, 2012). Essentially, storyboards show activity, position, variation, perspective, and performance by sampling them. The illustrator's task is to both incubate and execute the sketch, which is experimental. The storyboard artist (student, teacher, or researcher) analyzes and visualizes the action or dynamics (Halligan, 2015). Storyboards can explore any perspective, from microbial interaction and a microbe's point of view to a grand evolutionary all-in-one page view. Storyboards help artists organize seemingly multilayered, excitable events, assisting them in conceptualizing weblike interactions. The "right image point of view" has been an important aspect of scientific illustration and was pioneered by Santiago Ramón y Cajal (Fiorentini, 2009) and others (Babayan, 2021). The right point of view assisted Ramón y Cajal as he intertwined metaphors with drawing, leading up to his neuron doctrine.

Oddly, storyboards have not been used to teach biology or plan labs, flesh out ideas, or offer alternative views. Until now, biology classroom experiences do not appear to spend much time on student understanding of change, the slowing down of events, or development of the necessary artistic skills to capture those events. In this work, we offer a wide range of storyboard applications in the biology classroom.

Storyboards have been common throughout science and art but have simply remained disconnected from biology teaching. Other terms are often used in storyboarding, including *thought balloons, splash pages, panels, plots, dialogue balloons, layouts,* and *bursts*. All these designs of the storyboard process assist in bringing the biological concept to life. "*Narrative techniques or imaginary tools make people see things, or see them differently, yet they can also be employed to confirm preexisting or lingering emotion. The infusion of images is always strategic, as concepts of genetics can be altered or confirmed by images and imaginations*" (VanDijik 1998). For biology, transformation and change are underlying themes of life, and while storyboards are often used in marketing to sell ideas, in biology they can be used to unearth ideas.

○ Contemplative Biology & Storyboarding

The pace of education and research has been accelerated by technology, and much of the process has been removed. Storyboards can help restore that process and provide a balance of technology and personal, unique experience. Contemplative learning addresses the slower-paced experiences, as a mind needs time to process, explore, question, and develop ideas (Webster-Wright, 2013). A variety of activities in a classroom lend to a greater variety of skills and more opportunities for a diverse student body. "*Technology and new digital media tools can enhance student learning; however, the opposite also can be true*" (Wood 2020). Storyboards allow students to step away from constant connection to digital media and offer a learning format that may actually enhance their critical thinking experiences when using technology. As a learning strategy, storyboarding is well suited for biological processes, particularly immense time periods in evolution and small-scale molecular realms of surreal abstraction. A storyboard experience can connect those long expanses in time with the molecular realm when rendered in varying perspectives. "*Students often report misconceptions and learning difficulties associated with various concepts especially those that exist at a microscopic level, such as DNA, the gene and meiosis as well as those that exist in relatively large time scales such as evolution*" (Mnguni, 2014). Merely viewing or interacting in unsophisticated ways with visualized concepts is not enough to inculcate a topic conceptually for the student (Latour, 1986). It has been noted that too much technology and graphics can actually confuse students further. "*Visual models such as diagrams and animations are then used to represent these phenomena at a larger scale so as to assist students with construction of content knowledge*" (Dori & Barak, 2001). Schönborn and Anderson (2010) argue that students and teachers need to develop visualization skills to work effectively with visual models. The overuse of technology in school and everyday life may also create a dependency that stunts the development of other skills affecting memory and visualizing (Sandu, 2020). The purpose of storyboards and paper-based activities, such as sketching for artists, is to develop visualization skills through actively creating (Halligan, 2013). Neither art theory nor art education can increase or instruct these skills, which is why repetitive practice and frequent hands-on experiences are essential to becoming an artist (Halligan, 2013).

Students may misinterpret graphs and visualizations or explanations in the text, the presentations, or from Google searches, as students rush to find the "right answer." Storyboarding and sketching for the storyboard offer a deliberate focus and a critical evaluation of information. This aspect of biology, perhaps of all learning, is fundamental but rapidly diminishing due to technology. The reflective and insightful experiences of slowly processing information and weighing out the concepts in one's own mind have been, in the past, the hallmark of good science and teaching in general (Shapiro et al., 2015). The arts and drawing can provide this ready-made, preexisting skill set to alleviate the fast-paced flood of new information if educators and students are willing to develop the skill and some patience. While there is a measure of interest in the arts in biology, the introduction of the arts and drawing can start with a storyboard format, which is a simple way to isolate and retain an image of biological activity or process. While storyboarding is often thought of as more of a topic confined to comic strips, movie scene planning, and structuring the images of a narrative, its role may change with an application to the delivery of biology content.

Dynamic action is another critical component of visualizing a biological system. Minor artistic accentuations, movement lines, perspectives, strokes, waves, and angles, as well as implied force and gravity, all play a role. It may not be challenging to draw the sequential steps of mitosis in ready-made circles, which are the most common lab experiences students have with mitosis, but if we consider mitosis as a dynamic interplay of the local environment and chromosomes as a dynamic genome, then illustrating such events as cytokinesis becomes more challenging. For example, we could conceptually grow the storyboard affecting a cell's life. Teachers can bring actual research articles and link them as subtopics in the mitotic storyboard, generating important questions and considerations regarding cell cycle disruption and cancer or endocrine-disrupting chemicals and gene expression during mitosis. This could change the outcome of a normal cell-cycle storyboard. For students, this type of artistic problem is also a biological one. To understand cytoplasm, plasma membrane structure, and cytokinesis, they might need to use metaphors comparing the separation of cytoplasm to a "drawstring bag" filled with gelatin and appeal to our sensory experiences with different textures, substances, and their subsequent qualities. We also must consider what molecular properties underly shape changes, tensions, and expansions and what properties contribute to particular movements. From the example in cytoplasmic movement, we would sketch based on observations and experiences of what reminds us of cytoplasm since most of us have only seen it under a light microscope or read about it. This requires attention to visceral experiences and "feelings" we have about squishy, soft, malleable organic substances. We sketch and sketch until we are satisfied with the emerging concept and the skill. As an illustrator, one internalizes the expressed action to depict it better. This level of sensory integration and understanding is rarely addressed in education. According to Gardner, this may be considered a kinesthetic experience (Brualdi Timmins, 1996); however, it is much more complex.

Reinforcement of the biological concept through storyboarding would come from the students and teacher making preliminary visual sketches and moving to more deliberate ones. The repetition and closeness with the content and phenomena allow for considerable evaluation and reevaluation. This is what gives storyboarding its powerful contemplative element. Contemplation, focus, and intensive noticing are the pillars of good observational skills. While the mindfulness movement may be affecting educational realms in minor ways, good observation is being mindful of what we have given attention to.

○ Why Storyboarding Is Important for Teaching Biology: A Case Study from Linus Pauling

> *"Pauling's model-building approach was novel to both crystallography and biological research. It became crucial to the investigations of protein structure, allowing precise visualization of the molecular arrangements and interactions hitherto hidden."*
> Lily E. Kay (1992)

If you're a science student but have not come across Linus Pauling's contributions, this is a great way to become acquainted with the two-time Nobel Prize–winning biochemist. What does Linus Pauling have to do with storyboarding? Pauling presents us with an excellent historical example of how simple storyboarding can offer a visual argument and a visual hypothesis, a completely theoretical one or one developed from various data, as is the case of Pauling's research into protein structure. Pauling is an exciting example for students because he combined wet-lab research (gel electrophoresis) with an essentially artisanal model-building skill, biochemical experiments, visual tools, and—ultimately culminating from his work—a storyboarded hypothesis. Students and teachers might argue that they are not artists and cannot draw, but we should note that Pauling was not technically considered an artist/illustrator and that his drawings, although simplistic, were important drawings or sketches and embodied his conceptual framework of proteins. Immediate expert drawing skills or computer modeling software are not necessary to make a coherent argument through storyboarding. With his antibody drawings, Pauling was able to bridge an enormous gap that existed in genetics back in the 1930s and '40s, answering the question of how limited genetic material could give rise to an endless number of antibody variations. The prevailing view that genetics were immutable was dashed by Pauling's "instructional model" of antigen/antibody interactions (Mead & Hager, 2001).

Pauling visualized shapes and geometry and was heavily influenced by quantum mechanics, which is evident in his small storyboarding cartoon of the specificity of antibodies, particularly in the antigen's malleability. The complex of antigen/antibody together ushered in a new view of protein-protein interactions. Pauling's proposed flexible antigens were transported to the sites of an antibody (immunoglobulin), where shape changes took place (Cambrosio et al., 2005). The illustration of a polypeptide's naïve state as a simple line implies a myriad of folding options due to the nature of the amino acid's weak bonds, lending to an oscillation between bonds illustrated in enlarged images. This was another focus and another collaboration in Linus Pauling's vast interests. It is in that simple wavy line (polypeptide) that Pauling positions his hypothesis. The illustrations imply the potential resourceful variability and shape change in the future protein (antibody complex), one that enables it to morph itself around the antigen (the visual climax), produce a die, and cast specificity (the not-so-final storyboard image). The "quantum wobble" refined Pauling's questions about protein diversity, particularly the enormous numbers of antibodies that can be generated from a finite pool of amino acids, but his storyboarding doesn't stop there, and like all good comics, he zooms our focus into the fuzzy crevices of the newly folded antibody. He shifts the viewer's proximity and introduces some of the details of the complementarity of molecules. In this closeness, we can imagine the three-dimensional configurations of the amino acid polypeptide chains that exhibited the greatest complementarity to the antigen and that go on to become the functional antibody. The progression of the storyboard fluently takes us through Pauling's condensed hypothesis. Pauling's thought experiment on paper is an invitation to imagine a world to which we have no access. A fragment of the unknown dynamic protein world becomes graspable through his scientific and artistic methods.

Pauling's scope of research was wide, but it was protein structure and behavior that fascinated him the most. Essentially Pauling was using paper and pencil tools to elucidate the structures and relationships of these complex biological substances (Nye, 2001). What Pauling did with his "paper" argument of antigen/antibody was bring the energetic and invisible protein to life. According to the author of "Arguing with Images," Pauling essentially changed the mental perception of genetics by taking "a flatland of instructions—a code" and replacing it with three-dimensional shapes (Cambrosio et al., 2005)" Pauling was trying to do more than present a mechanism of immune system interfaces, though; he was proffering a way of thinking about living biochemical systems as complementarities, an idea that was a major component of Bohr's duality and variability of the electron (Bohr, 1950). He recognized the pattern of reciprocity and interdependence at the biochemical-molecular level, a quality that essentially exists at all levels of living systems, from molecules to ecosystems. Through the storyboard, Pauling captured both complementarity and malleability of protein structure and behavior.

Although Pauling was deeply disillusioned that biology textbooks overlooked his broad overarching idea of biological complementarity, which was beautifully visualized in his storyboard, Pauling may have gifted science something far more meaningful: the flexibility of the storyboard and the artistic process. Pauling had many successes and failures, but this is often the case with prolific efforts and another reason why sketchbooks are important. So, our takeaway message from Pauling's work is that the storyboard presents a stage for smaller mechanism clarification and, in that storyboard, an all-inclusive relationship-based model of biological systems can also emerge. For our purposes, Pauling's use of the storyboard and subsequent pencil sketches (see Figures 2 and 3) and even paper model making imply that many facets of investigation and discovery can be facilitated through the synthesis of an artistic process and a scientific investigation and that neither is ever complete. They also remind us not to underestimate the power of "pencil-and-paper thinking."

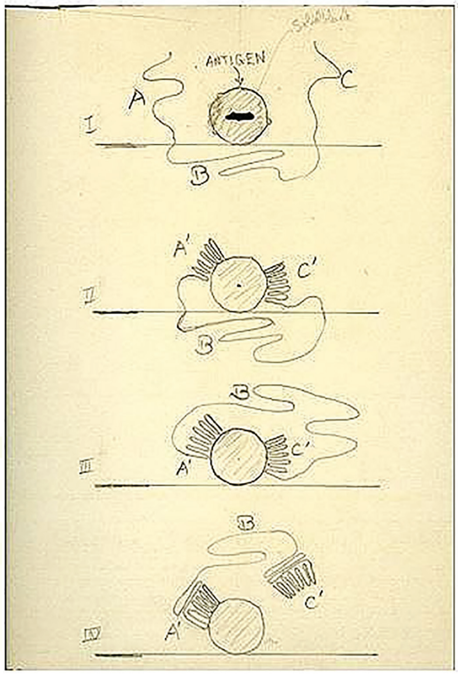

Figure 2. Pauling's antigen/antibody storyboarded cartoon, 1940. http://scarc.library.oregonstate.edu/coll/pauling/proteins/pictures/sci7.001.5-drawing.html.

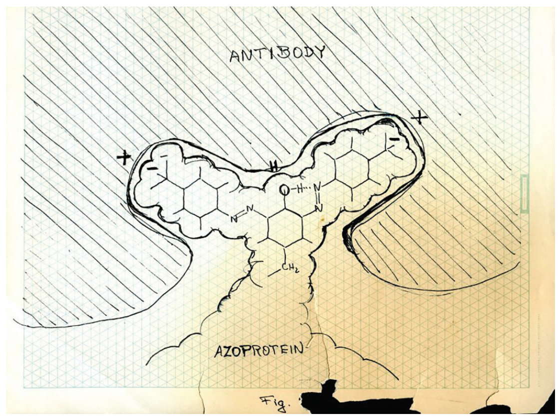

Figure 3. Pauling's close-up sketch of the shape and chemistry of an antibody as it makes contacts with its specific antigen. http://scarc.library.oregonstate.edu/coll/pauling/proteins/pictures/sci7.001.5-drawing.html.

○ The Flexibility of the Storyboard, Sketching & Paper Tools

> *"Student engagement is what happens when students have the responsibility to make choices and are encouraged to take chances and be creative."*
> Jaime E. Martinez (2017)

Employing different types of materials to draw with, varied paper textures, and alterable lighting also create different perspectives. They help us imagine abstract worlds that we mentally "scale up" or down, make slower or faster, varying our worldview. The benefit of using different artistic tools is that each one creates a unique experience that invites choice and creativity. When we observe illustrations of molecular worlds in proteins, DNA, histones, or even the vast landscape of the cell, we accept that there is a source of light similar to what we see and that colors exist. When we speak of "interactions," we have to imagine what those might actually look like. For abstract conditions, the storyboard lets our imaginations play with possibilities, bearing in mind that what we are interpreting, even if it is informed by research, a concept that is invented. Sketching is a major component of storyboarding, and sketching with pencil and paper has always been the go-to for formulating ideas, doodling, experimenting with drawing tools, and testing our own integration of an idea. Simple tools work well for storyboarding as the brain processes its sensory experiences with paper and pencil differently from computer technology or typing. Despite all the digital tools available, storyboard artists still prefer to work with paper and pencils (Lee & Buscema, 1984). The brain's processing of incoming sensory input requires a refractory period, which is exactly what a notebook and a pencil provide (Fish & Scrivener, 1990).

To plan a storyboard, we need to think about sequences of events, translating words into actions. This is followed by the choice of artistic materials, the desired effect, and what perspective suits interpretation best. Chalk and ink (pens, markers, charcoal) invite a varied sensory palette that allows the brain to recalibrate and compare. The textures of paper, the fluid nature of ink, the softness of pastel are more complex and varied than keyboard, plastic mouse, pen. While this is a topic for another article, the tools of a notebook and pencil are inexpensive and invite innovation; when less is done *for you*, more is required *of you*.

What other aspects of the storyboard can be used for biology education? Even if the storyboard seems too arts-based for many biology teachers, another attraction exists: the storyboard as a studying aid. Students often have many ways of accommodating their personal studying style. Some students use index cards, others highlighters, some watch videos, and others write and rewrite chapters from textbooks. All of these have some activity level in them, but storyboarding, because of its sketching and drawing foundation, involves a level of intimate engagement that none of the other methods have. Consider the example of photosynthesis; most students are asked to memorize the anatomy of chloroplasts, identify parts, and provide basic information about light and dark reactions. To do this, students study the diagrammatic image in their textbooks or watch a video. A page out of storyboarding, however, particularly if it is illustrated on the board by the teacher, would take the same image of the chloroplast and dissect it slowly. This is simply done by having the student draw and redraw a chloroplast in multiple perspectives and even illustrate the chloroplast dividing in an active mesophyll cell. By illustrating, coloring, and then imagining the events of photosynthesis, students create their own study aid. Storyboards can be used also as an assessment tool to confirm knowledge.

○ Storyboards & a Lesson from the Sunday Comics

Examples of history are abundant in the use of the arts for biological or scientific research, but storyboarding or "comic stripping" is not as easy to locate. It is likely that many scientific notebooks contained sequential diagrams or drawings of step-by-step experiments or slowed down biochemical or biological processes, but their availability is scarce. If we consider that dynamic processes are essentially movies with our perspective as the observer, we begin to see the value of integrating storyboarding into biological thinking. Processes of biological nature are created by either animators or the animator in our heads.

What are some of the possible storyboards we can create with students? Viruses attaching to bacterial or other cells, injecting their nucleic acids, hijacking or slipping into the cellular web, and navigating the host to produce protein coats, spikes, capsids, nucleic acids, attachment arms (see Figures 4 and 5). The obvious

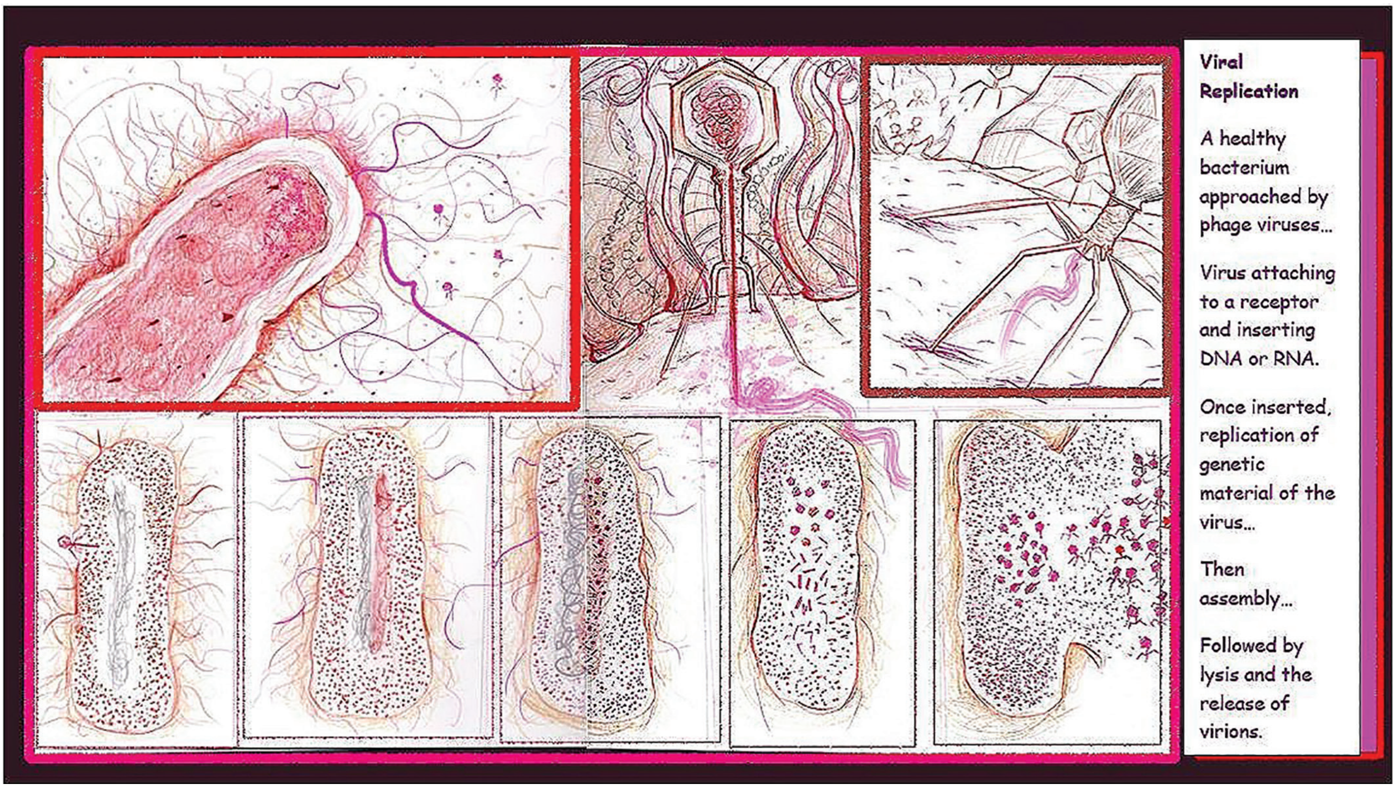

Figure 4. In this figure a typical viral infection pathway is recreated through a storyboard. Essential "steps" of viral replication are sequentially illustrated with a few different perspectives that are of interest. This allows a close examination of each step in the hypothesis of viral replication and the terms associated with it. Choice of design, color, and style are up to the individual making the storyboard and can imply a variety of conceptual and speculative ideas.

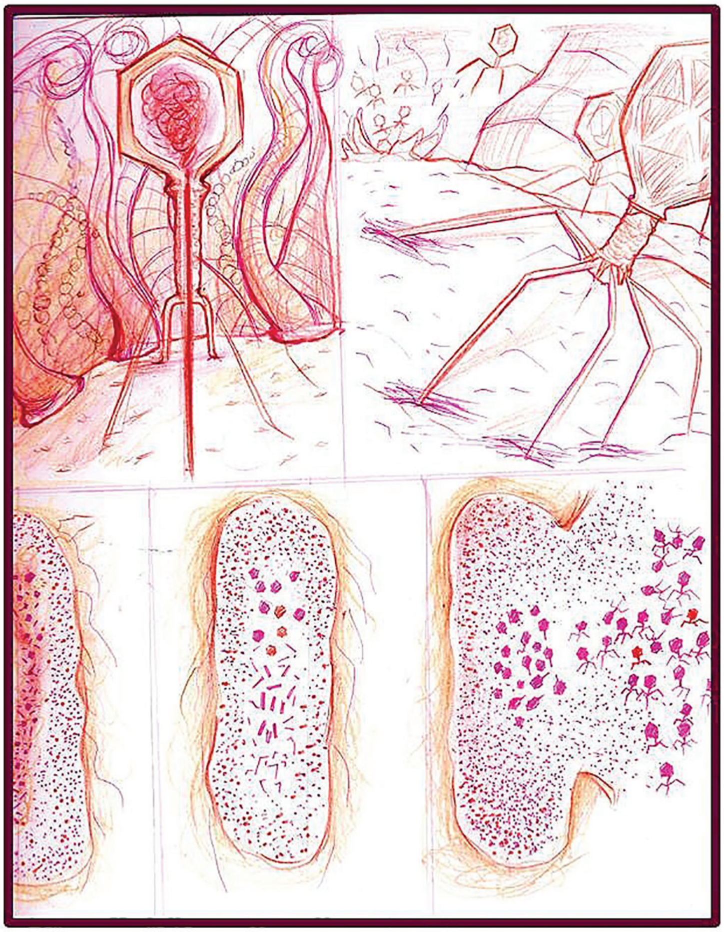

Figure 5. A close-up of the storyboard shows attention to the bacterial surface and the anatomy of the virus. By illustrating this, students are actively engaged in studying. Details become necessary to create an attractive, accurate, and interesting story. Students may also reflect on the processes they are learning and develop original thoughts and ideas about hypotheses and biological theories. Colored pencils were used to create this one-page storyboard.

storyboard of cell reproduction, succession, embryological development of any structure or form, life cycles, metamorphosis, protein synthesis, phagocytosis, cell-mediated endocytosis, wound healing, gene regulation (macroevolution, adaptive radiation, microevolution, horizontal gene transfer, budding, apoptosis, fission, speciation, mutation, translocation, duplications, independent assortment, crossing over, epistasis, epigenetics, the sliding filament theory, and the list goes on. Explore any topic in biology, and it becomes abundantly clear that almost any biological concept can be storyboarded.

○ Storyboarding for Lab Activities

Lab experiments are great hands-on experiences, and bench work is designed to create conceptual or theoretical knowledge tangibly. Too often, however, because of time constraints, deliberate exploration of each step in the lab sometimes becomes just busywork. Dissections, DNA extractions, chromatograms, and plating, all of which require a degree of procedure, can easily be storyboarded. When students have to explore and examine each step they are taking, deliberate action is guided by the storyboard cell, which allows the action to unfold. Sometimes even with surgeons, or other skilled professionals, storyboarding the surgery can positively impact the outcome because it prepares the surgeon with the particular case at hand and with possible or likely problems and outcomes while reinforcing technique and procedure. We suggest choosing a lab that students have difficulty with and providing students with templates for storyboarding to test this idea. For homework, have students storyboard with images and words related to the experiment the day before doing it.

○ Storyboarding for Bioinformatics & Computational Software

We ask students to assimilate technology without the consideration of constant updates, new software, and changing delivery formats such that both students and teachers have little opportunity to actually get to know what they are using, how it works, or why it's changing, and if that change is really necessary or beneficial. Many times, just as in a lab, students and teachers are just "going through the motions," trying to keep pace with rapid technology changes. This does not teach skills but rather fragments them. Another great advantage of storyboarding the use of the software is that it provides a safe experience, one without the frustrations of making mistakes or creating bigger issues. Whenever your lesson plan stagnates or hits a difficult point of understanding, try employing a storyboard format before having students engage with software. Storyboarding can be an intermediate between reading about how something works and actually using

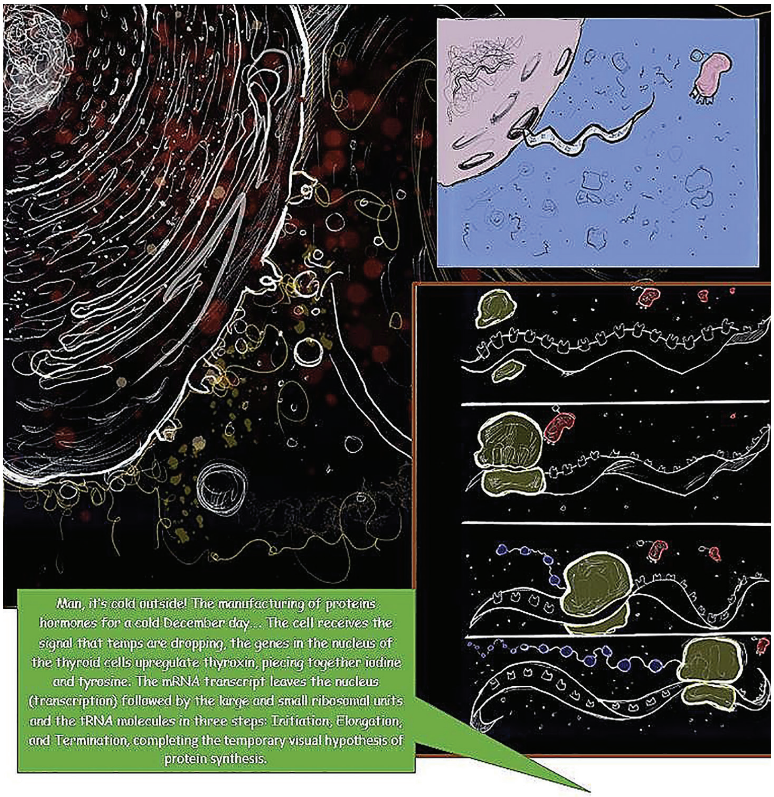

Figure 6. A brief storytelling introduction about hormone production of thyroxine in colder climates leads to a personal interpretation of proteins synthesis. The introduction engages and sets the scene for each student's unique interpretation of transcription and translation. Pen, ink, and marker were used to create this one-page storyboard.

it. Tutorials are important to watch, but again, this is passive, and tutorials are made to show successful experiences in and with ideal conditions, which often do not reflect individual predicaments. Storyboarding reinforces concepts and allows for active experience and even creativity with software. Students can choose which templates, colors, or art materials they would like to use to create their storyboards. They can also keep the storyboards in personal notebooks or sketchbooks as go-to references. Sometimes software that appears effortless to use is quite complicated; even Microsoft Word involves complex, convoluted processes to produce simple changes. For biology class, a student might be asked to search on a database like GenBank, use software like MEGA (Kumar et al., 2018), or explore the TimeTree of life online (Kumar et al., 2017). As a preliminary activity, students can storyboard the directions and analyze each step at a time on paper. Often students want to get through a lab or an experience and finish it fast to give credit for sketching out directions. Along the way and while using the program, students can then add notes to their storyboard, indicating where something went wrong or how they solved a problem. Many students cut and paste data, sequences, graphs, and graphics without knowing what they are actually working with and why they are doing it.

○ Conclusion

Embracing the fundamentals of art processes in biology can initiate a cascade of creative, thought-provoking, and focused inquiry into the biological processes. Educators and students become equipped to establish and institute their individual learning with storyboards, paper models, and sketching. The focused and deliberate use of storyboards for analyzing motion, dynamics, processes, morphologies, phenotypes, and environments makes them an ideal format for interactive, engaging, and contemplative biology experiences. With simple tools, students can familiarize themselves with the components of a lesson plan, a lab, or a computational program, advancing an understanding of the activity's terminology and purpose. For an authentic STEAM experience to develop though, students and educators must embrace developing classical drawing skills, as it is these skills that hone observation of biological phenomena, particularly dynamic processes and change in forms. Storyboards can offer multiple perspectives, stimulate interesting questions, and help develop biological drawing and visualization skills necessary for a more complete and personal understanding of complex biological phenomena.

○ Acknowledgments

This work was supported by research grants from the U.S. National Science Foundation (ABI 1661218 and 1932765) to S.K.

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